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DESIGN AND OPTIMIZATION OF SUBMERSIBLE PUMP IMPELLER

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ABSTRACT

Open well submersible pumps are relatively new product in the family of centrifugal pumps. These pumps are immersed in the working fluid unlike the conventional centrifugal pumps. Optimization of the design of the impeller without changing the diameter is one difficult task as it would not allow much increase in the head, hence the diameters are kept constant and the objective was formulated to improve the head claimed by the industry, by minimising the head losses that are particular to the impeller. The impeller design parameters are optimized using optimization algorithms such as GA,SA,PS etc and the optimized values are used for design of new impeller. This design is then tested using commercially available CFD package Ansys CFX with k-epsilon, k-epsilon EARMS and SST turbulence models.

Key words: Non-traditional optimization, Shape optimization, Turbo machinery, Centrifugal pump.

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1. INTRODUCTION

General methodologies to improve design of conventional systems are: inverse design and optimization. Inverse design involves by defining the pressure distribution along the blades of the impeller. In any pump system, there are always losses which are added to the overall performance of the system [1]. These losses can be categorized as: Electrical, Hydraulic and Mechanical losses. An attempt has been made in this research work to improve the head of the pump, by minimizing the hydraulic losses. Another way of defining the optimizing the design is by reducing the losses involved in the system. Evolutationary mathematical optimization techniques such as Genetic Algorithm, Particle swarm optimization etc., are used for design optimization [2]. Which involve non-linear mathematical model and found to be effective in terms of time, accuracy & maximixed result.

2. LITERATURE AND INFERENCES

There has been numerous work carried out on optimization of impeller design of the pump. [1] uses, Theoretical model is described to predict the centrifugal pump performance when its impeller is equipped with splitters. Methodology used compares the constructional differences of the pump equipped with splitter blades as compared with the conventional pump. Hydraulic loss analysis were done to predict the performance of centrifugal pumps. [3] has found the losses associated with the performance of the pump and used to theoretically estimate the head of the pump and validate with experimentation. [4] uses, artificial bee colony algorithm for optimization of the impeller and has shown an improvement of 3.59% in efficiency. [5] has done study on the performance of the pump by varying the outlet angle as the design parameter. [6] has used trial and error method and optimized the head of the pump using CFD analysis.[7] has used orthogonal array and varied the design parameters and found their effectiveness in the head of the pump through CFD.

2.1. OBSERVATIONS FROM LITERATURES

- 1-D study is used for vane design.
- Larges radius makes more head.
- Changes in the outlet vane angle changes the efficiency of the impeller.
- Optimum vane angle is achieved step by step with different CAD models
- Rotational momentum equation has to be solved for turbo machines in CFD

3. METHODOLOGY

From the research gap postulated in section 2, The procedure to optimize the pump design is discussed in the following section. A market available pump of 5HP rating was taken for study and it was found that the submersible pump has a delivery head of 25m, Hence objective was formulated to improve this delivery head. First and foremost the head formulation for the pump with losses will be done. This is followed by CFD analysis of the existing design. The second part was to choose the optimization technique to use for optimization, those chosen techniques will be used for optimization. The final part involves the CFD analysis of the optimized design of the impeller.

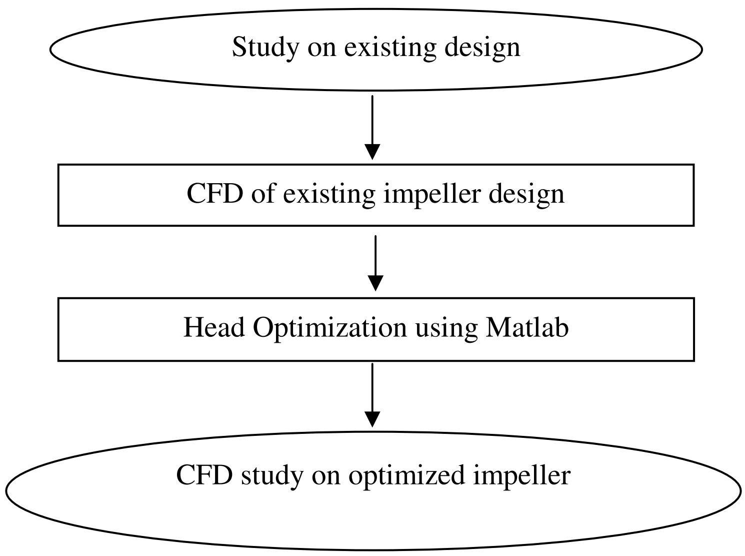

Figure 1 Methodology

4. RESEARCH METHODOLOGY

4.1. Head Formulation

In order to optimize the head, the head of the pump has been formulated. From Euler's equation for turbo machinery the head of the centrifugal pump without whirl is given as [4]:

$$H_{th} = \frac{U2Cu2}{g} \tag{1}$$

The head losses identified are:

Circulation head Loss: As described in [1], circulation is caused by increase in relative velocity at inlet and decrease in relative velocity at the outlet of the impeller ,

$$H_c = \frac{(1-\mu)U2^2}{g} \tag{2}$$

Inlet incidence loss: has been calculated as described in [1]

$$H_i = \frac{0.7(U1-Cu1)^2}{2g} \tag{3}$$

Impeller friction loss: A s described in [5] due to surface of the impeller and vanes the there would be emery dissipation and this would be given as

$$H_f = \frac{b2(D2-D1)(C1+C2)^2}{2Sin\beta 2\times Hr\times 4g} \tag{4}$$

Where

The hydraulic radius $H_r = \frac{b2\left(\frac{\pi D2}{Z}\right)Sin\beta 2}{b2+\left(\frac{\pi D2}{Z}\right)Sin\beta 2}$

Hence the net total head with losses will be:

$$H_{net} = H_{th} - H_c - H_i - H_f \tag{5}$$

4.2. CFD Analysis

In the process of design, the pre final step would be the simulation process that would be CFD analysis of the impeller to find the head for the duty point discharge. In order to validate the optimized model the initial step would be to simulate the existing design and check with the mathematical model prepared. Initially the existing design impeller was measured for the design parameters and is follows:

- Inlet diameter(D_1) : 76mm
- Outlet diameter(D_2) :160.4mm
- Inlet blade angle(β_1) : 30^0
- Outlet blade angle (β_2): 30^0
- Inlet impeller width (b_1): 18mm
- Outlet impeller width(b_2) : 10.2mm
- No.of vanes(Z) : 6

The pre processing was done with the rotational velocity of 2810rpm (motor rated) and boundary conditions were

- Inlet : 1 atm
- Outlet: Duty point mass flow rate (6.05kg/s)

Studies show there has been few turbulence models that are to be used for centrifugal pump simulation [6]. Hence most popular turbulence models are selected, they are:

- K-epsilon
- K-epsilon EARMS
- Shear stress Transport model (SST)

These models were tested using Ansys CFX and their results were found.

4.4. Optimization Methods

For the proposed problem, design optimization would be to performed to improve the duty point head (25m). As described in Section 3.2, since Eq-5 involves nonlinear terms it would be of choice to use non-traditional optimization techniques. According to the work done in [2], it was identified to use 3 popular solvers namely:

- Genetic algorithm (GA)
- Particle swarm optimization (PSO)
- Pattern search (PS)

4.4.1. Genetic Algorithm

Genetic Algorithm (GA) is a search algorithm based on the conjecture of natural selection and genetics. The algorithm is a multi-path that searches many peaks in parallel, and hence reducing the possibility of local minimum trapping. GA works with a coding of parameters instead of the parameters themselves. The coding of parameter will help the genetic operator to evolve the current state into the next state with minimum computations. GA evaluates the fitness of each string to guide its search instead of the optimization function. There is no requirement for derivatives or other auxiliary knowledge. GA explores the search space where the probability of finding improved performance is high.

4.4.2. Particle swarm Optimization

Particle swarm optimization (PSO) is a population-based stochastic approach for solving continuous and discrete optimization problems. In particle swarm optimization, simple software agents, called *particles*, move in the search space of an optimization problem. The position of a particle represents a candidate solution to the optimization problem at hand. Each particle searches for better positions in the search space by changing its velocity according to rules originally inspired by behavioral models of bird flocking. Particle swarm optimization belongs to the class of swarm intelligence techniques that are used to solve optimization problems.

4.4.3. Pattern Search

Pattern search finds a local minimum of an objective function by the following method, called polling. In this description, words describing pattern search quantities are in bold. The search starts at an initial point, which is taken as the current point in the first step:

1. Generate a pattern of points, typically plus and minus the coordinate directions, times a mesh size, and center this pattern on the current point.

2. Evaluate the objective function at every point in the pattern.

3. If the minimum objective in the pattern is lower than the value at the current point, then the poll is successful, and the following happens:

3a. the minimum point found becomes the current point.

3b. the mesh size is doubled.

3c. the algorithm proceeds to Step 1.
4. If the poll is not successful, then the following happens:
4a. the mesh size is halved.
4b. if the mesh size is below a threshold, the iterations stop.
4c. Otherwise, the current point is retained, and the algorithm proceeds at Step 1.

5. RESULTS & DISCUSSION

5.1. Existing Design Performance Evaluation

With the dimensions of the impeller measured the losses were estimated. The duty point mass flow rate was given as the outlet boundary condition, CFD analysis was done for the three specified turbulence models. Following are the result by theoretical and CFD analyses.

Table 1 Losses developed in the impeller

Discharge (m^3/s)	**Theoretical Head (m)**	**Head Losses**			**Net Head (m)**	**Head claimed by the industry (m)**
		Circulation head (m)	**Inlet Incident Loss (m)**	**Frictional head (m)**		
0.00605	38.29	14.8634	0.2121	0.0179	23.1967	25

It can be seen that the circulation head contributes to the maximum this is due to the fact that the speed is taken is constant [8]. Inlet incident loss contributes less, this is because of the fact that, the whirl velocity involved in the loss (Eq-3), is dependent on the discharge and the same is applicable for the frictional loss (Eq-4).

5.2. Simulation of Existing Design

From literature [6], it could be found that there are few most common turbulence models used for centrifugal pump simulation. The existing design was tested for accurate models listed in [6].

Table 2 Turbulence model comparison

Turbulence model	**Head (m)**
K-epsilon	38.22
K-epsilon EARMS	38.15
SST	38.6

From table 2 we find that the K-epsilon model is much closer to the net theoretical head (38.29m), hence it would be convenient to use the same for simulation purpose of the optimized model.

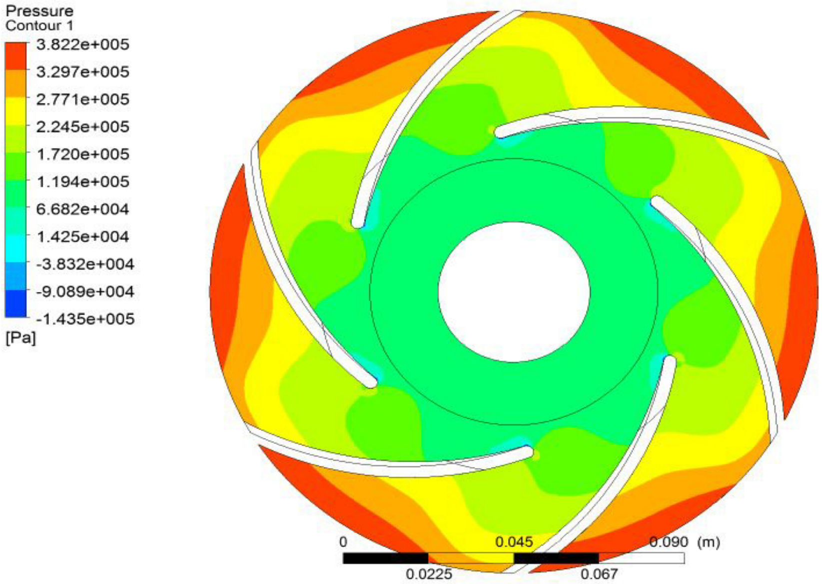

Figure 2 Simulation of existing design

From fig 2, it is evident that the solution has converged properly, And that the head has converged to the value of 38.22m at the outlet.

5.4. Optimization Computation

The problem described in section 4 is coded in MATLAB and the above mentioned algorithms were used for optimization. Twenty trails were performed as described in [2]. and the average for each parameter were taken as the design parameters from the each solver. The net head was calculate for each parameters from the solvers.

Table 3 GA result table

Trial .No	b_1 (m)	b_2 (m)	B_1 (deg)	B_2 (deg)	Z
1	0.01971	0.011205	32.22278	27.00377	6.99811
2	0.0198	0.011219	31.72584	27.03114	6.998719
3	0.01979	0.011193	32.23771	27	6.994889
4	0.019032	0.011217	32.97973	27.0132	6.999988
5	0.019741	0.011195	29.51032	27.0003	6.99833
6	0.019677	0.011184	30.28991	27.00998	6.997203
7	0.019786	0.011215	32.99356	27	6.998972
8	0.018781	0.011204	32.42831	27.00353	6.989807
9	0.01979	0.011193	32.98755	27.00222	6.992399
10	0.019737	0.011216	32.9468	27.00058	6.998951
11	0.016839	0.011172	32.87619	27.01357	6.999877
12	0.019782	0.011174	32.99054	27.0041	6.990989
13	0.01978	0.011118	32.45682	27.01457	6.99466
14	0.019654	0.011168	32.73113	27	6.999756
15	0.019784	0.011205	32.02996	27.04251	6.996918
16	0.019771	0.011202	32.96209	27.02306	6.998907
17	0.019768	0.011148	32.51205	27.00315	6.997679
18	0.019154	0.011216	32.99998	27.12727	6.998472
19	0.019762	0.011144	32.77239	27	6.99693
20	0.019592	0.011178	31.64257	27.00767	6.998228

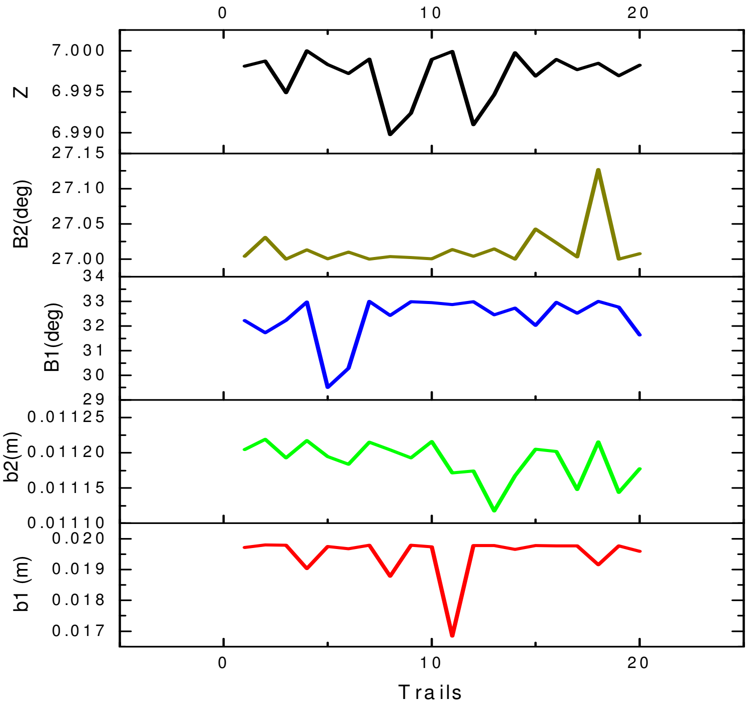

Figure 3 Performance of Genetic algorithm

From the fig 3 we see that there are not much variations in inlet width and outlet angle parameter but No.of vanes, outlet width and inlet angle show considerable variations during trail runs.

Table 4 PS result table

Trial. No	b_1(m)	b_2(m)	B_1(deg)	B_2(deg)	Z
1	0.018	0.0102	30	30	6
2	0.018	0.0102	30	30	6
3	0.018	0.0102	30	30	6
4	0.018	0.0102	30	30	6
5	0.018	0.0102	30	30	6
6	0.018	0.0102	30	30	6
7	0.018	0.0102	30	30	6
8	0.018	0.0102	30	30	6
9	0.018	0.0102	30	30	6
10	0.018	0.0102	30	30	6
11	0.018	0.0102	30	30	6
12	0.018	0.0102	30	30	6
13	0.018	0.0102	30	30	6
14	0.018	0.0102	30	30	6
15	0.018	0.0102	30	30	6
16	0.018	0.0102	30	30	6
17	0.018	0.0102	30	30	6
18	0.018	0.0102	30	30	6
19	0.018	0.0102	30	30	6
20	0.018	0.0102	30	30	6

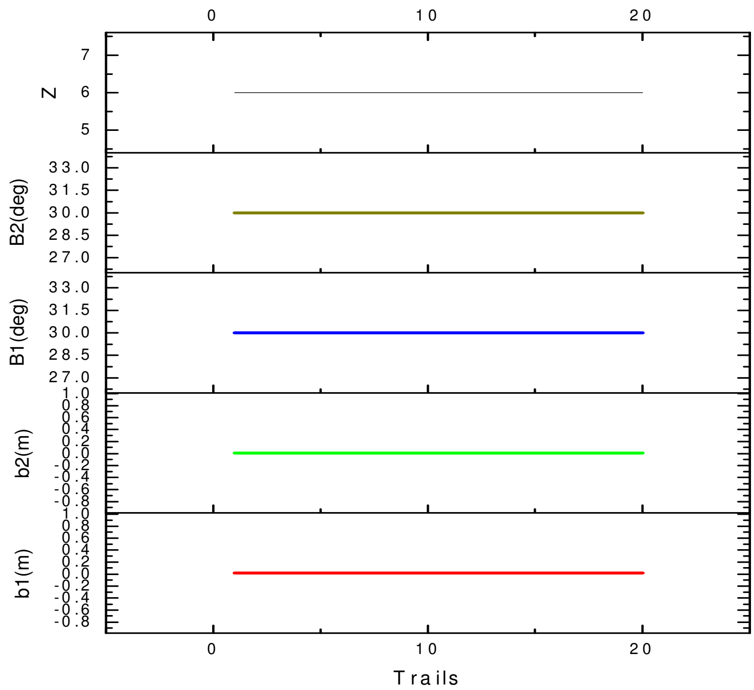

Figure 4 Performance of Pattern Search algorithm

From Fig 4, it is evident that there has not been any change in the existing design that the Pattern Search solver identifies and there has not been any change in the head of the pump.

Table 5 PSO result table

Trial. No	b_1(m)	b_2(m)	B_1(deg)	B_2(deg)	Z
1	0.0198	0.01122	32.99999	27	7
2	0.0198	0.01122	33	27	6.999999
3	0.0198	0.01122	33	27	7
4	0.0198	0.01122	32.97518	27	7
5	0.0198	0.01122	32.99998	27	7
6	0.0198	0.01122	32.99998	27	7
7	0.0198	0.01122	32.98641	27	7
8	0.0198	0.01122	33	27	7
9	0.0198	0.01122	32.99998	27	7
10	0.0198	0.01122	32.99999	27	7
11	0.0198	0.01122	33	27	7
12	0.0198	0.01122	32.99837	27.00047	7
13	0.0198	0.01122	32.99995	27	7
14	0.0198	0.01122	33	27	7
15	0.016914	0.011219	33	27	7
16	0.016914	0.01122	32.99999	27.00002	6.999999
17	0.0198	0.01122	32.99998	27	7
18	0.0198	0.01122	32.99999	27	7
19	0.0198	0.01122	33	27	7
20	0.0198	0.01122	32.99992	27.00016	7

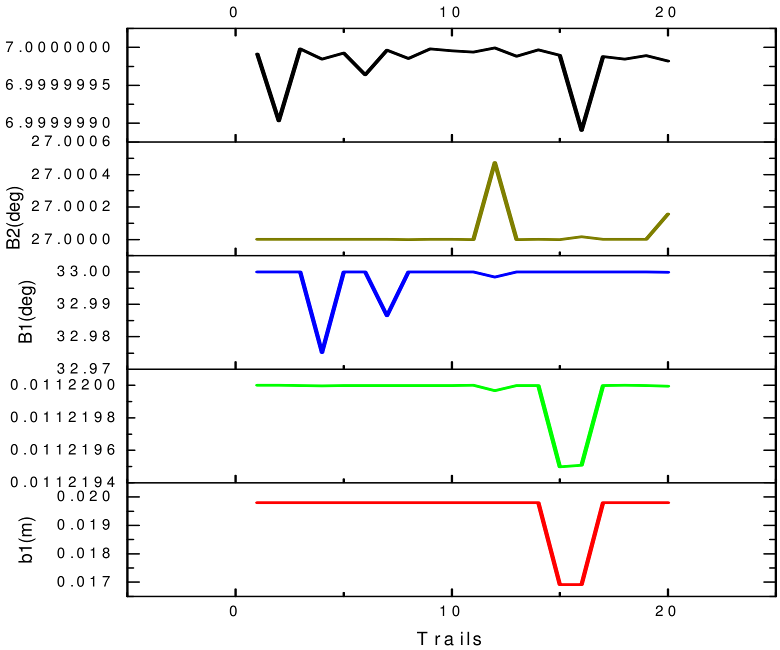

Figure 5 Performance of Particle swarm Optimization algorithm

From Fig 5, it is identified that there is not been much variations in any of the parameter and the solver solves more evenly than that of GA and PS, The head for these parameters the head of the pump increases significantly.

Table 6 Optimized parameters

Method	Inlet width-b_1 (m)	Outlet width-b_2 (m)	Inlet angle-β_1 (deg)	Outlet angle-β_2 (deg)	No.of blades-Z	Head (m)
Existing Design	0.018	0.0102	30	30	6	23.2
GA	0.0195	0.011	32	27	7	29.36
PS	0.018	0.0102	30	30	6	23.2
PSO	0.0195	0.011	33	27	7	29.37

From table 6 it is identified that the parameters by PSO gives the maximum head of 29.37m which states that there has been an improvement of 26.6% in the head. Hence these parameters are taken for simulation purposes.

5.4. Theoretical Characteristics of Optimized Design

The parameters from the optimization were used on the mathematical model developed and the losses are estimated.

Table 7 Theoretical head of optimized design

Discharge (m^3/s)	Theoretical Head (m)	Head Loss			Net Head (m)
		Circulation head (m)	Inlet Incident Loss (m)	Frictional head (m)	
0.00605	41.103	11.5677	0.1428	0.0181	29.37

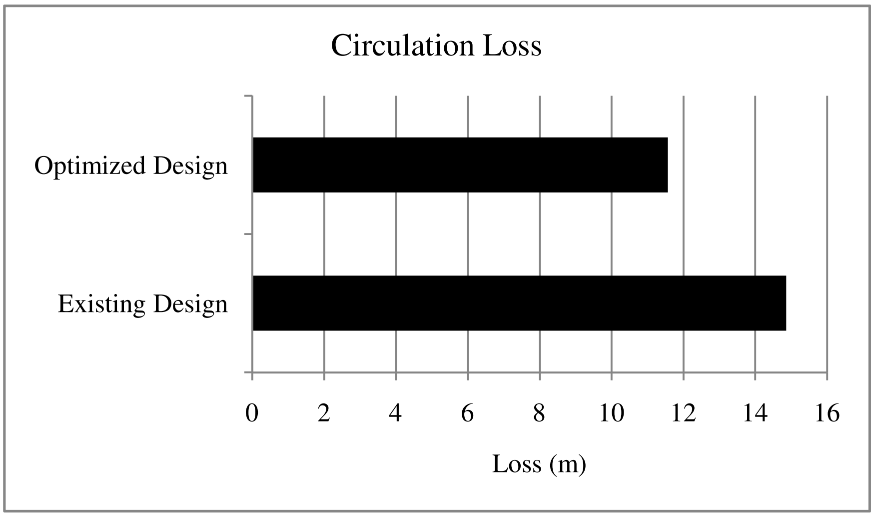

Figure 6 Circulation Loss comparisons

From fig 6, it is understood that there is has been significant decrease in the circulation head for the pump by 22.17%. The decrease is due to the increase in the slip developed in the flow at outlet.

Figure 7 Inlet incident loss comparison

From the fig 7, it is seen that there has been decrease in the inlet incident loss, at duty point the decrease is 32.67%. This is due to the fact that the outlet whirl velocity is dependent on the discharge and so it is observed as in Eq-3.

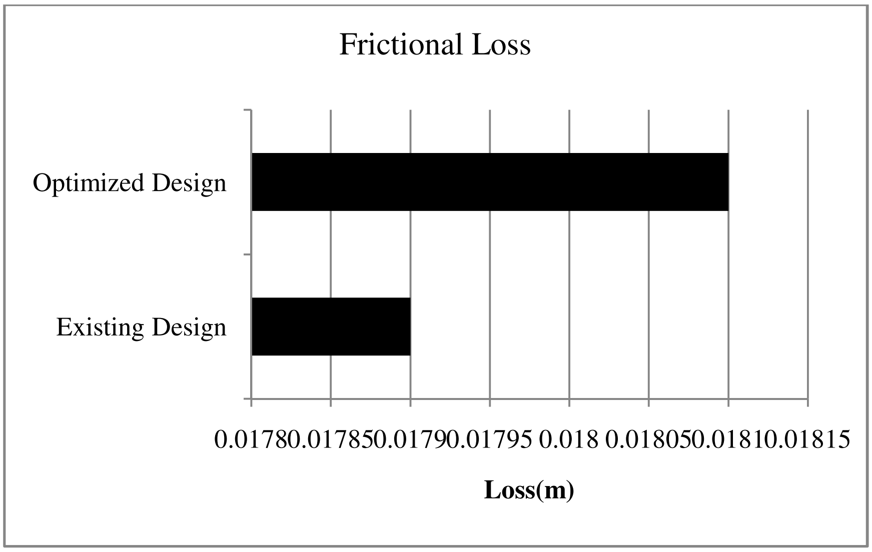

Figure 8 Frictional head loss comparison

From the fig 8, it is found that there has been an increase in the friction head, this is due to the fact that there is a decrement in the outlet angle and at duty point the increase is 1.11%.

5.5. Simulation of the Optimized Design

As described in the section 3.4 k-epsilon turbulence model was used to simulate the model. and it was found that there is 2.36% improvement in the head.

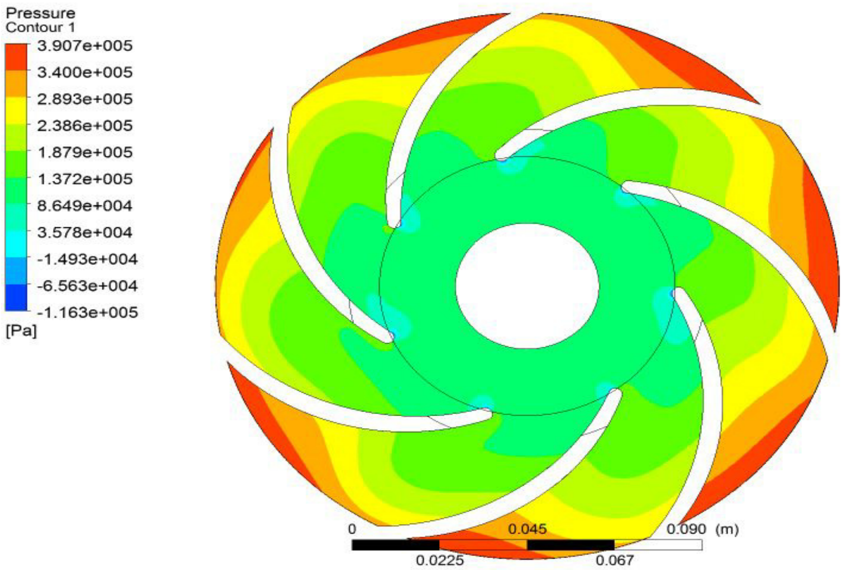

Figure 9 Simulated result of optimized impeller

This improvement of 2.36% in the head of the pump is mainly due to increased number of vanes and the increased slip of the flow at the impeller outlet.

The work is wrapped up by comparing the improvement in the performance and the changes in the parameters. It could be shown in table 8 that the changes in the parameters are within the ±10% variation [3]. All the means of evaluating the performance has shown the improvement and is listed in table 9.

Table 8 Design parameters of the impeller

Parameters	Existing dimension	Optimized dimension
Inlet width (m)	0.018	0.0195
Outlet width (m)	0.0102	0.011
Inlet angle (deg)	30	33
Outlet angle (deg)	30	27
No.of blades	6	7

Table 9 Optimized Head

Method	Percentage improvement (%)
Theoretical	17.48
Simulation	2.36

6. CONCLUSION

The pump selected had a power rating of 5HP , it was observed that the existing pump can give a duty point delivery head of 25m and discharge of 0.00605m^3/s. It was desired to improve the delivery head of the pump, hence design optimization was adopted. The impeller dimensions were noted and used in mathematical model to theoretically calculate the head of the pump. The mathematical model developed was used as objective function and constrains were the five design parameters with $\pm$10% from the existing dimensions. Most popular algorithms as specified in [2] were used include: Genetic algorithm (GA), Particle swarm optimization (PSO), Pattern search algorithm (PS). These algorithms were run for 20 trails as in [2] and the average of these runs were taken as the optimized value of design parameters. Among three PSO algorithm gave maximum head of The head was calculated for these parameters and theoretically it was improved by 17.48%. The changes in losses were:

- Circulation loss decreased by : 22.17%
- Inlet incident loss decreased by 32.67%
- Frictional loss increased by 1.11%

The increase in frictional loss is due to the fact that there is decrease in the outlet angle. Simulation of the head was done for the pump with K-epsilon model and it was found that there was an improvement by 2.36% .

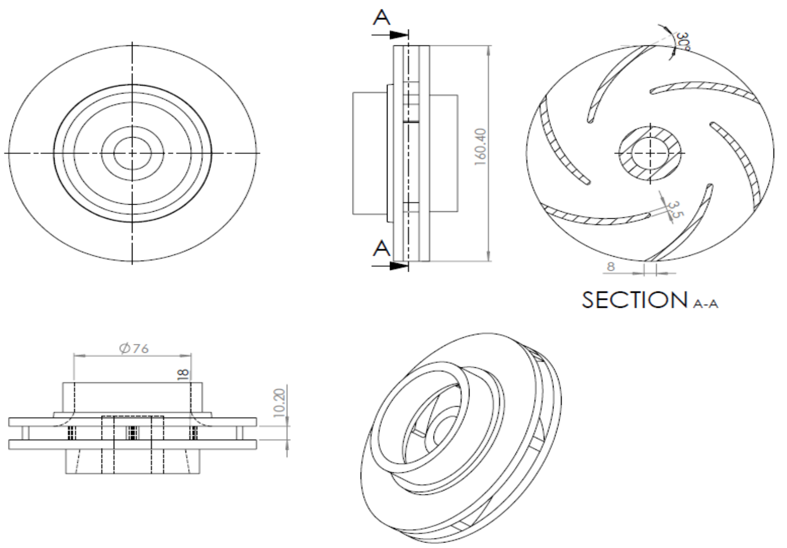

Figure 10 Existing impeller

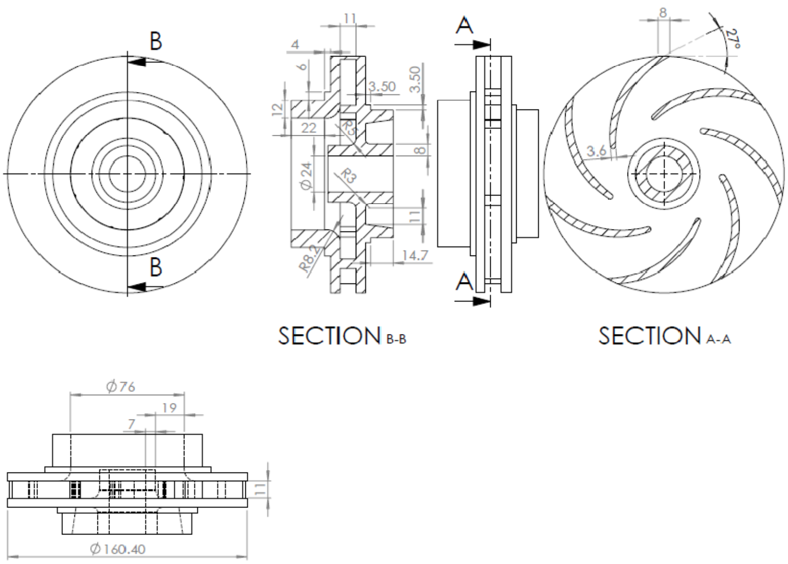

Figure 11 Optimized impeller

Figure 12 Existing and optimized impeller cut section

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